Woodward-Clyde

Engineering & sciences applied to the earth & its environment

June 13, 1995
C3M11Q

Mr. Brad Bradley
USEPA Region V, 5HS 11
77 West Jackson, 6th Floor
Chicago, Illinois 60604-3590

Dear Mr. Bradley,

As you requested, we are submitting our responses to comments on groundwater remediation options discussed in the Second Addendum to the Feasibility Study for the NL/Taracorp Superfund Site. Also attached is the supporting backup documentation for each response.

If you have any questions concerning any material included in this package, please call.

Very truly yours,

David L. Pate
Senior Project Geologist

encl.

cc: Eugene Liu
Kenneth Hagg

NL/Taracorp Superfund Site
Second Addendum to the Feasibility Study
Responses to Comments

Comment Number 1: From Illinois Environmental Protection Agency:

"The IEPA's main concern with the PP and the 2FS is the groundwater remedy. The $3 million estimate for groundwater remediation appears to be unrealistic. One extraction well may not cause a cone of depression large enough to control the migration of the contaminated groundwater. Contamination has been documented in wells on all sides of the pile. To be on the conservative side, the estimate should include costs for on-site treatment. Secondly, the proposal to discharge to the local POTW via the sewer system may pose problems. As you may know, Granite City has a combined sewer system. If any overflows exist between the POTW and the site, contaminated groundwater discharge to the sewers may occur only during dry weather periods. The sewer use charge imposed by the city may be subject to change and may become inflated because of their relationship with the agency. Also, the POTW may have problems handling the concentrations and/or the volume."

Response to Comment Number 1:

Commment Number 1 raises a series of points that are addressed in the order that they were presented.

1. Basis for cost estimate. The cost estimates quoted for the Second FS Addendum were based on discussions with drilling contractors, remediation contractors, equipment manufacturers, local POTW personnel, and experienced environmental professionals within WCC concerning a variety of scenarios.

   The effect of inflation and future cost increases is evaluated in Table 4-4 of the Second FS Addendum. Present worth costs over the projected 30 year life of the project are evaluated for discount rates of 3%, 5%, and 10%.

2. Number of wells required to create a cone of depression. The cost estimate assumes that from 1 to 3 pumping wells would be installed at the downgradient end of the site.

   Based on the our geologic understanding of the site, a saturated aquifer thickness of 90 feet, and a hydraulic conductivity of 10^{-2} cm/sec, or 212 gpd/ft^2, were assumed. Using these parameters, the radius of influence for each well should be approximately 1,800 feet.

   To achieve a capture width of 2,000 feet, or roughly the width of the industrial site along the strike of the groundwater gradient, both the Keely-Tsang equation (1983) and the method proposed by Grubb (1993) predict that approximately 230,000 gpd, or 160 gpm of withdrawal would be required to maintain an inward gradient for the industrial site.

   One eight inch well placed in the southwest part of the SLLR property could accomplish this. Pumping at approximately 160 gpm, the well could establish a cone of depression approximately 15 to 19 feet deep. The cone of depression would extend out laterally forming a parabolic zone of influence that would extend upgradient covering the entire site. Alternatively, up to three wells could be drilled and installed on the industrial site if a more pronounced cone of depression is deemed necessary. The cost estimate for this option included in the Second FS Addendum contains contingency funds for the installation of up to 3 extraction wells. Pump tests would be conducted after the first well is installed to verify that the performance matches the predictions.

3. Need for on-site treatment. The Granite City Sewer Use Ordinance (No. 3819) establishes an upper limit for total lead of 0.50 mg/L on water entering the POTW. The ordinance specifies that the monthly average shall not exceed this standard.

   The quarterly sampling data collected to date from the on-site monitoring wells indicates that the average total lead concentration in groundwater over the entire site is 0.099 mg/L, with only four out of 87 samples that have been collected to date exceeding the POTW limit. Since the average concentration is less than 20 percent of the POTW upper limit for lead, it seems unlikely that pre-treatment will be required.

4. Daily volume that the POTW can handle. Based on our calculations, a sufficiently large cone of depression is produced by pumping approximately 160 gpm, a volume of approximately 230,000 gallons per day would require disposal into the combined sewer system. Discussions with Mr. Ron Parente and Mr. Terry Kellahan of the Granite City POTW indicate that they have ample capacity to handle this volume.

5. POTW disposal fees. The costs to dispose of the pumped water into the POTW are based on the disposal rates quoted to WCC by the Granite City POTW. The rate system is graduated based on volume. As the volume increases, the unit rate goes down. Based on the unit prices quoted, the annual cost to dispose of the pumped groundwater would be approximately $77,000 per year. The annual disposal cost quoted in the Second FS Addendum of $67,000 per year is based on a withdrawal rate of 150 gpm. The revised cost of $77,000 per year is based on a withdrawal rate of 160 gpm or roughly 230,000 gallons per day.

6. Discharge constraints due to wet weather, or high water conditions. Any groundwater scenario involving pumping could have this problem. Mr. Ron Parente of the Granite City POTW indicated that this is a very infrequent occurrence. When problems due occur, they are localized is low lying areas flood-prone areas, and do not impact the entire system. Mr. Parente said that to the best of his knowledge the NL/Taracorp site was not one of these areas. Mr. Parente also noted that even in abnormally wet years, such as 1993 and 1995, there have not been any widespread problems.

Comment Number 2: From Louis F. Bonacorsi, Joseph G. Nassif, and Dennis P. Reis:

"4. Most importantly, U.S. EPA's proposed groundwater pumping remedy simply would not work. The elevated metals concentrations in the samples collected by U.S. EPA were due to high turbidity in the samples. In other words, the metals concentrations in the samples were caused by metals in the sediments, not by metals dissolved in the groundwater. When groundwater recovery wells are installed as part of a groundwater pumping system, they must be designed to minimize the sediments in the extracted groundwater to avoid damage to pumps and other equipment. Thus, the extracted groundwater would at most contain low levels of metals while the vast majority of the metals would remain tied to the sediments and would be immobile and unrecoverable."

Response to Comment Number 2:

The issues raised by Commment Number 2 are addressed in the order that they were presented.

1. Elevated metals concentrations due to high turbidity in groundwater samples. Starting in late 1993, the procedures for collection of groundwater samples were modified to reduce the turbidity created by the surging action of a bailer. Most of the wells, except for a few of the slow recharging shallow wells, were purged and sampled using a 2 inch OD Grunfos submersible pump. After the required purge volume was removed (5 well volumes), the pumping rate was reduced to the minimum rate for the pump (approximately 100-300 ml per minute) and the required unfiltered samples were collected. This procedure results in a noticeable reduction in sample turbidity, and approximates what withdrawals due to pumping would resemble. Using this approach, 10 wells have still yielded at least one sample with a lead concentration in excess of the IEPA standard and the USEPA MCL.

2. It should be noted that the primary purpose of developing a cone of depression by pumping is not to remediate the aquifer. Rather, the purpose is to control off-site flow of contamination. This approach would be very effective with regard to containment.

Comment Number 3: From Citizen's Group:

"It was very disappointing that the U.S. EPA was unable to answer questions regarding the proposed remedy at the public hearing held on this subject. Concerning the cost estimates for treating the ground water, the following questions need answers:

1. How many new wells will be bored?

2. How many gallons per day will be pumped?

3. How much will treatment of this waste cost per year?

4. Can the local wastewater treatment plant handle this volume of material without affecting the classification of the sludge produced at the plant?

5. Is the cost estimate to drill new wells, construct,if necessary, a pretreatment facility, pump, transport and treat the wastewater for 30 years accurate?

Response to Comment Number 3:

The issues raised by Commment Number 3 are addressed in the order that they were presented.

1. How many new wells will be bored?

   Based on our analysis of the aquifer characteristics, a single pumping well will be able to create a sufficient cone of depression in the water table to control off-site migration of groundwater. Fifteen additional piezometers would be installed to adequately monitor the cone of depression that the pumping well would develop.

   However, this will need to be verified by pump testing after the well is installed. The cost estimate contains sufficient contingency to allow installation of up to three pumping wells if the pump tests indicate additional wells are required.

2. How many gallons per day will be pumped?

Based on our calculation using both the Keely-Tsang equation (1983) and the method proposed by Grubb (1993), we predict that approximately 230,000 gpd, or 160 gpm of withdrawal would be required to maintain an inward gradient for the industrial site.

3. How much will treatment of this waste cost per year?

Based on the disposal unit rates quoted by the Granite City POTW (see attached), and assuming that the pumping rate is approximately 160 gpm, or 230,000 gpd, the annual cost for disposal are estimated to be approximately $76,000.

4. Can the local wastewater treatment plant handle this volume of material without affecting the classification of the sludge produced at the plant?

Based on the contaminant limits for total lead of 0.5 mg/L quoted in the Granite City Sewer Use Ordinance (No. 3819), and on the results of several years of groundwater sampling data (average total lead concentration of 0.099 mg/L), it does not appear that the disposal of the groundwater produced from the NL/Taracorp site will add enough contaminants to require a reclassification of the sludge produced by the wastewater treatment plant.

5. Is the cost estimate to drill new wells, construct,if necessary, a pretreatment facility, pump, transport and treat the wastewater for 30 years accurate?

The cost estimates quoted for the FS were based on the best available information. WCC personnel discussed a variety of scenarios with drilling contractors, remediation contractors, equipment manufacturers, the local POTW, and experienced environmental professionals within the WCC organization.

The effect of inflation and future cost increases is evaluated in Table 4-4 of the FS Addendum. Present worth costs over the projected 30 year life of the project are evaluated for discount rates of 3%, 5%, and 10%.

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TELEPHONE MEMORANDUM *PROJECT NUMBER:* C3M11Q

DATE: 12/15/93 *TIME:* 2:45 pm

TO/FROM: Ron Parente

COMPANY/LOCATION: Granite City Regional Sewer System

PHONE NUMBER: (618)452-6230

RECORDED BY: Cynthia Pavelka

PROJECT: N.L. Taracorp

NOTES:

CFP called to determine applicable unit rates for disposal of groundwater into the POTW. CFP described the pumping scenario to Mr. Parente, and the reasons why this volume of water would need to be pumped.

Estimate that we would be pumping approximately 150 gallons per minute, or roughly 200,000 gallons per day (26,750 cubic feet per day) into the sewer system.

Rates are based on a sliding scale according to volume. The rate is lower for higher volumes. Rates are in terms of cubic feet per calendar quarter.

Volume rates are as follows:

1st	2,100 ft^3	\$0.86 per 100 ft^3	per quarter
next	36,900 ft^3	\$0.86 per 100 ft^3	per quarter
next	36,000 ft^3	\$0.83 per 100 ft^3	per quarter
next	81,000 ft^3	\$0.80 per 100 ft^3	per quarter
next	81,000 ft^3	\$0.76 per 100 ft^3	per quarter
next	162,000 ft^3	\$0.73 per 100 ft^3	per quarter
next	1,098,000 ft^3	\$0.66 per 100 ft^3	per quarter
next	1,500,000 ft^3	\$0.59 per 100 ft^3	per quarter

There is an additional charge of \$0.04 per 100 ft^3 for monitoring for contaminant levels that may require pretreatment before being discharged into the system.

There is also an initial application fee of \$200.

Granite Sewer Use Ordinance No. 3819

2.1 General Discharge Prohibitions

No user shall contribute or cause to be contributed, directly or indirectly, any pollutant or wastewater that will interfere with the operation or performance of the POTW. These general prohibitions apply to all such users of a POTW whether or not the user is subject to National Categorical Standards or any other National, State, or local Pretreatment Standards or Requirements. A user may not contribute the following substances to any POTW:

a) Any liquids, solids, or gases that by reason of their nature or quantity are, or may be, sufficient either alone or by interaction with other substances to cause fire or explosion or be injurious in any other way to the POTW or to the operation of the POTW. At no time shall two successive readings on an explosion hazard meter, at the point of discharge into the system (or at any point in the system), be more than five percent (5%) nor any single reading over ten percent (10%) of the Lower Explosive Limit (LEL) of the meter. Prohibited materials include, but are not limited to to the following: gasoline, kerosene, hexane, naphtha, benzene, toluene, xylene, ethers, alcohols, ketones, aldehydes, peroxides, chlorates, perchlorates, bromates, carbides, hydrides, sulfides, and any other substance that the City, State, or EPA has identified to the user as a fire hazard or a hazard to the system.

b) Solid or viscous substances that may cause obstruction to the flow in a sewer or other interference with the operation of the wastewater treatment facilities such as, but not limited to the following: grease, garbage with particles greater than one half inch (1/2") in any dimension, animal guts or tissues, paunch manure, bones, hair, hides, or fleshings, entrails, whole blood, feathers, ashes, cinders, sand, foundry sand, core sand, spent lime, stone or marble dust, metal, glass, straw, shavings, grass clippings, rags, spent grains, spent hops, waste paper, wood, plastics, gas, tar, asphalt residues, residues from refining or processing of fuel or lubricating oil, mud, glass grinding, or polishing wastes.

c) Any wastewater causing corrosive damage or hazard to structures, equipment, or personnel of the wastewater facilities, but in no case discharges having a pH lower than 5.0 or greater than 10.0 at any time.

d) Any substances that cause an excessive chlorine demand in the POTW effluent.

e) Any wastewater containing toxic pollutants in sufficient quantity, either singly or by interaction with other pollutants, to injure or interfere with any wastewater treatment process, constitute a hazard to humans or animals, create a toxic effect in the receiving waters of the POTW, or to exceed the limitation set forth in a Categorical Pretreatment Standard. A toxic pollutant shall include but not be limited to any pollutant identified to Section 307(a) of the Act.

f) Any noxious or malordorous liquids, gases, or solids that either singly or by interaction with other wastes are sufficient to create a public nuisance or hazard to life or are sufficient to prevent entry into the sewers for maintenance and repair.

g) Any substance that may cause the POTW's effluent or any other product of the POTW such as residues, sludges, or scums, to be unsuitable for reclamation and reuse or to interfere with the reclamation process. In no case shall a substance discharged to the POTW cause the POTW to be in non-compliance with sludge use or disposal criteria, guidelines, or regulations developed under Section 405 of the Act; any criteria, guidelines, or regulations affecting sludge use or disposal developed pursuant to the Resource Conservation and Recovery Act, the Clean Air Act, the Toxic Substances Control Act, or State criteria applicable to the sludge management method being used.

h) Any substance that will cause the POTW to violate its NPDES Permit or the receiving water quality standards.

i) Any wastewater with objectionable color not removed in the treatment process, such as, but not limited to, dye wastes and vegetable tanning solutions.

j) Any wastewater containing heat in amounts that will accelerate the biodegradation of wastes, causing the formation of excessive amounts of hydrogen sulfide in the wastewater sewer or inhibit biological activity in the wastewater treatment facilities, but in no case shall the discharge of heat cause the temperature of the influent to the treatment facilities to exceed 40°C (104°F).

k) Any pollutants, including oxygen-demanding pollutants (BOD, etc.) released at a flow rate and/or pollutant concentration that a user knows or has reason to know will cause interference to the POTW.

l) Any wastewater containing more than 200 mg/l of fats, oils, or grease (FOG).

m) Any garbage that has not bee properly shredded, i.e., no particle greater than one-half inch in any dimension.

n) Any waters or wastes containing suspended solids of such character and quality that unusual attention or expense is required to handle such materials at the POTW.

o) Any wastewater containing any radioactive wastes or isotopes of such half-life or concentration as may exceed limits established by the Superintendent in compliance with applicable State or Federal regulations.

p) Any wastewater that causes a hazard to human life or creates a public nuisance.

When the Superintendent determines that a user is contributing to the POTW any of the above prohibited substances in such amounts as to interfere with the operation of the POTW, the Superintendent shall: 1) advise the user of the impact of the contribution on the POTW; and 2) assist in developing procedures for such user to correct the interference with the POTW (see Section 8 for enforcement procedures).

2.2 Federal Categorical Pretreatment Standards

No person shall discharge or cause to be discharged to any wastewater facilities, wastewaters containing substances subject to an applicable Pretreatment Standard promulgated by EPA, the State of Illinois, or the local POTW in excess of the quantity prescribed in such applicable standard except as otherwise provided in this section. Compliance with such applicable pretreatment standards shall be within 3 years of the date the standard is promulgated; compliance with a categorical pretreatment standard for new sources shall be required upon promulgation.

Upon application by an industrial user, the Superintendent shall adjust any limitation on substances specified in the applicable pretreatment standards to consider factors relating to such user that are fundamentally different from the factors considered by EPA during the development of the pretreatment standard. Requests for and determinations of a fundamentally different adjustment shall be in accordance with Federal law.

The Superintendent shall notify any industrial user affected by the provisions of this section and establish an enforceable compliance schedule for each.

2.3 Specific Pollutant Limitations

No user shall discharge wastewater containing more than the maximum amounts of the following listed pollutants:

Pollutant	Concentration (mg/l)
Arsenic	0.5
Barium	11.0
Cadmium	1.2

Chromium	9.0
Copper	3.0
Lead	0.5
Manganese	7.0
Mercury	0.001 daily max 0.0005 monthly ave
Nickel	2.6
Selenium	3.0
Silver	0.4
Total Phenols	2.5
Zinc	5.0
* Cyanide	0.25

* Except as otherwise specifically provided, proof of violation of the numerical standards of this pollutant shall be on the basis of one or more of the following averaging rules:

1) No monthly average shall exceed the prescribed numerical standard.

2) No daily composite shall exceed two times the prescribed numerical standard.

3) No grab sample shall exceed five (5) times the prescribed numerical standard.

Terms in this section shall have the following meanings:

1) The monthly average shall be the numercial average of all daily composites taken during a calender month. A monthly average must be based on at least three (3) daily composites.

2) A daily composite shall be the numerical average of al. grab samples, or the result of analysis of a simgle sample formed by combining all aliquots, taken during a calender day. A daily composite must be based on at least three (3) grab samples or three (3) aliquots taken at different times.

3) A grab sample is a sample taken at a single time. Aliquots of a daily composite are grab samples only if they are analyzed separately.

2.4 <u>City's Right of Revision</u>

The City reserves the right to establish by ordinance more stringent limitations or requirements on discharges to the wastewater disposal system if deemed necessary to comply with the objectives presented in Section 1.1 of this Ordinance.

2.5 <u>Excessive Discharge</u>

TABLE 4-4
PRESENT WORTH ANALYSIS
NL/TARACORP SUPERFUND SITE

Alternative	Capital Costs Year 0	Annual O & M Costs	Present Worth of Costs Over 30 years 3%	5%	10%
Solid Media – Main Industrial Area					
M-A: Source Removal to On-site Landfill	$4,510,000	$18,700	$4,880,000	$4,800,000	$4,690,000
M-B: On-site Treatment & Disposal	$28,700,000	$20,100	$29,100,000	$29,000,000	$28,900,000
M-C1: Off-site Treatment and Disposal	$64,800,000	$0	$64,800,000	$64,800,000	$64,800,000
M-C2: On-site Treament & Off-site Disposal	$34,600,000	$0	$34,600,000	$34,600,000	$34,600,000
M-D: On-site Sorting, Treatment; Off-site Recycling	$87,400,000	$0	$87,000,000	$87,400,000	$87,400,000
Solid Media – Remote Fill Areas					
RF-A: On-site Treatment and Disposal	$1,010,000	$17,200	$1,350,000	$1,270,000	$1,170,000
RF-A: On-site Treatment & Off-site Disposal	$999,000	$17,200	$1,340,000	$1,260,000	$1,160,000
RF-A: Off-site Treatment and Disposal	$1,110,000	$17,200	$1,450,000	$1,370,000	$1,270,000
RF-B: On-site Treatment and Disposal	$2,020,000	$0	$2,020,000	$2,020,000	$2,020,000
RF-B: On-site Treatment & Off-site Disposal	$2,180,000	$0	$2,180,000	$2,180,000	$2,180,000
RF-B: Off-site Treatment and Disposal	$2,610,000	$0	$2,610,000	$2,610,000	$2,610,000
Groundwater Media					
G-A: Monitoring and Natural Attentuation	$53,600	$57,800	$1,190,000	$940,000	$598,000
G-B: Pump & Dispose to local POTW	$466,000	$165,000 *	$3,710,000	$2,990,000	$1,990,000
G-C: Slurry Wall with Pump & Disposal to local POTW	$16,600,000	$97,800	$18,500,000	$18,100,000	$17,500,000
Solid Media – Adjacent Residential Areas					
Remediation with On-site Disposal	$13,600,000	$0	$13,600,000	$13,600,000	$13,600,000
Remediation with Off-site Disposal	$15,100,000	$0	$15,100,000	$15,100,000	$15,100,000
Drum Disposal	$11,200	$0	$11,200	$11,200	$11,200

* – The annual costs for the first two years for the Groundwater Media Alternative B will be $225,000 and $200,000, respectively.

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TABLE 3–16

PRELIMINARY COST AND TIME ESTIMATES

GROUNDWATER MEDIA – ALTERNATIVE G–B

Main Industrial Area – Pump & Dispose to local POTW

ITEM	QUANTITY	UNITS	UNIT COST	TOTAL COST
DIRECT CAPITAL COSTS				
– MAIN INDUSTRIAL AREA PUMP & TREAT				
Recovery Well Construction	1	LS	100,000	$100,000
Pump/Plumbing/Electrical wiring	1	LS	165,000	165,000
System Start–up	1	LS	10,000	10,000
– REMOTE FILL AREAS				
Install and Develop Monitoring Wells	10	EACH	2600	26,000
SUBTOTAL				$301,0[illegible]
Mobilization (10% of subtotal)				$30,100
SUBTOTAL CONSTRUCTION COSTS				$331,100
INDIRECT CAPITAL COSTS				
–CONTINGENCY				
(15% of Subtotal)				$49,665
–OTHER				
Administrative/Permitting (5% of Total)				$16,555
Surveying				$2,500
Engineering Design (10% of Total)				$33,1[illegible]
Construction Services (10% of Total)				$33,1[illegible]
SUBTOTAL				$134,940
TOTAL ESTIMATED CAPITAL COSTS				$466,040
ESTIMATED TIME TO CONSTRUCT (excludes design, bid, and admin.)				2 to 4 months

TABLE 3-16

PRELIMINARY COST AND TIME ESTIMATES

GROUNDWATER MEDIA - ALTERNATIVE G-B

Main Industrial Area - Pump & Dispose to local POTW

ITEM	QUANTITY	UNITS	UNIT COST	TOTAL COST
ANNUAL OPERATING & MAINTENANCE COSTS				
Groundwater Sampling Labor	13	Day	1000	13,000
Groundwater Sample Analysis	145	Ea	200	29,000
Misc. Equipment & Supplies	LS	LS	1000	800
Annual Monitoring Report	LS	LS	15000	15,000
ESTIMATED ANNUAL OPERATING & MAINTENANCE COSTS				$57,800
GROUNDWATER PUMP & TREAT OPERATION & MAINTENANCE COSTS				
Year 1	1	LS	100000	100,000
Year 2	1	LS	75000	75,000
Year 3-30	28	YR	40000	1,120,000
Groundwater Disposal to POTW	30	YR	77000	2,310,000
ESTIMATED PUMP & TREAT O & M COSTS				$3,605,000

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Sheet No. Of

File C31411 0

FOR Granite City, Cost Estimate for Pump-and-Treat

Made by RST Date 10-8-93

Checked by CFP Date 1-15-94

A. Capital Costs (3-well Recovery System)

Remedial Design $25K

Work Plan $15K

Permitting (... discharge to POTW) $5K

Public/Community Relations $10K

Drilling Subcontractor (labor, ... 3-... 15-... PVC piezometers) $100K

Pump, piping + electrical wiring $65K

On-site treatment unit $50K

... Oversite $...

System Start up $10K

Subtotal $400K

B. Operation - Maintenance (O+M)

Year 1 $100K

Year 2 $...K

Years 3-30 (40K/yr x 28 yrs) $1,120K

Subtotal $1,...K

Total Estimated Cost $1.7 mil

Surveying Unit Cost $100-$150/well Quantity = 18 wells

Total Cost = $150.00/well * 18 wells = $2,700 → $2,500

Woodward-Clyde Consultants

File C3M11Q

Made by KST Date 10-7-93

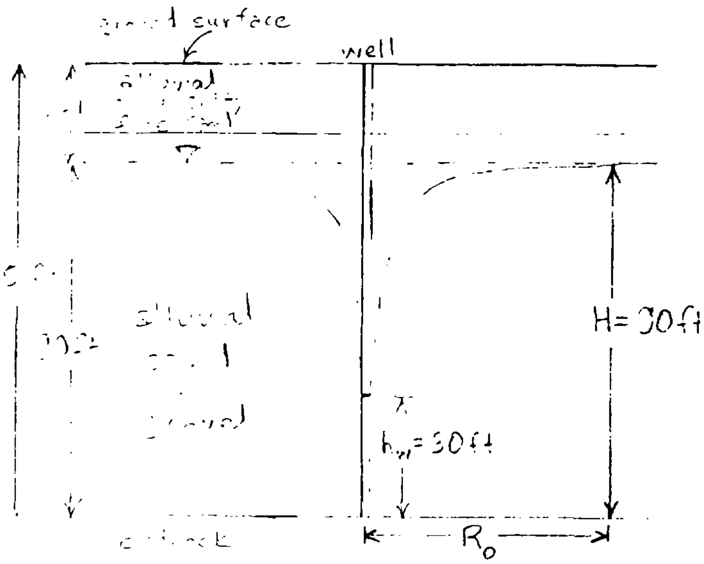
Checked by ______ Date ______

FOR Granite City

Rough/Cost Estimate of Groundwater Pump and Treat System for NL/Taracorp Site

Aquifer parameters:

- unconfined alluvial aquifer atop bedrock
- saturated thickness = 90 ft



- hydraulic conductivity, $K = 10^{-2}$ cm/sec = 212 gpd/ft²

Approximate radius of influence:

$$R_o = 3(H-h_w)(0.47K)^{0.5}$$

$$= 3(60\ ft)[(0.47)(212\ gpd/ft^2)]^{0.5}$$

$$= 1,797\ ft$$

Use [illegible] + Tsang (19[illegible]) equation

- [illegible] discharge necessary to achieve a capture width of 2,000 ft

W [illegible] $= Q / T (i)$

[illegible] discharge, gpd

T = transmissivity, gpd/ft $= K \cdot H$

[illegible] horizontal [illegible] gradient

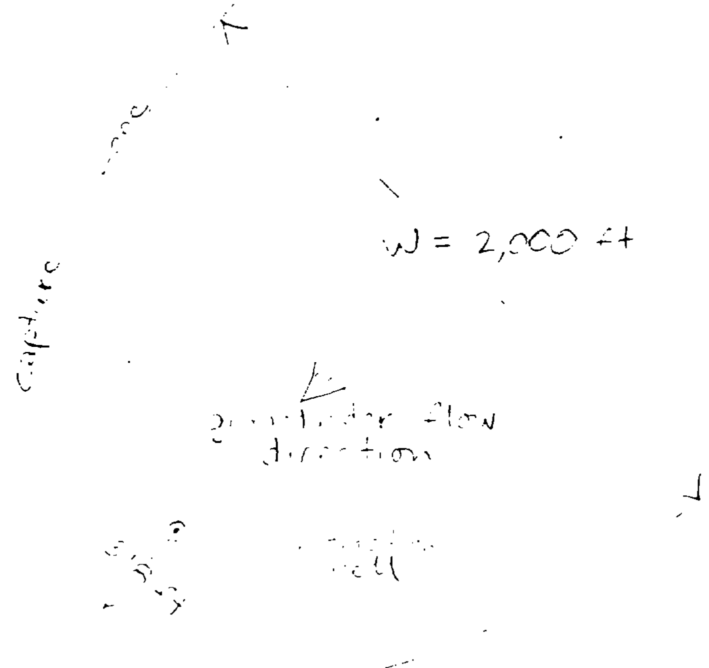
$Q = W \cdot T (i)$

$Q =$ ([illegible],000 ft) · (13,050 gpd/ft) (0.006 ft/ft)

$Q =$ [illegible] gpd = [illegible] gpm

[illegible] at W = 2,000 ft :

[illegible] / 2π = 3[illegible] ft



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Sheet No. [illegible] Of 4

File [illegible]

Made by KET Date 10-8-93

Checked by ________ Date ________

FOR Granite City

Calculate drawdown necessary to support discharge, $Q = 159$ gpm and capture width, $W = 2{,}000$ ft :

from Dawson + Istok (1991)

$$K = \frac{Q \ln (R / r_w)}{\pi (H^2 - h_w^2)}$$

$Q = 159$ gpm $=$ [illegible]

$\ln (R / r_w) =$ [illegible] 5.33

$$H^2 - h_w^2 = \frac{Q \ln (R / r_w)}{\pi K}$$

$H^2 - h_w^2 = 2{,}458$ - $3{,}053$; $H^2 = 8{,}100$

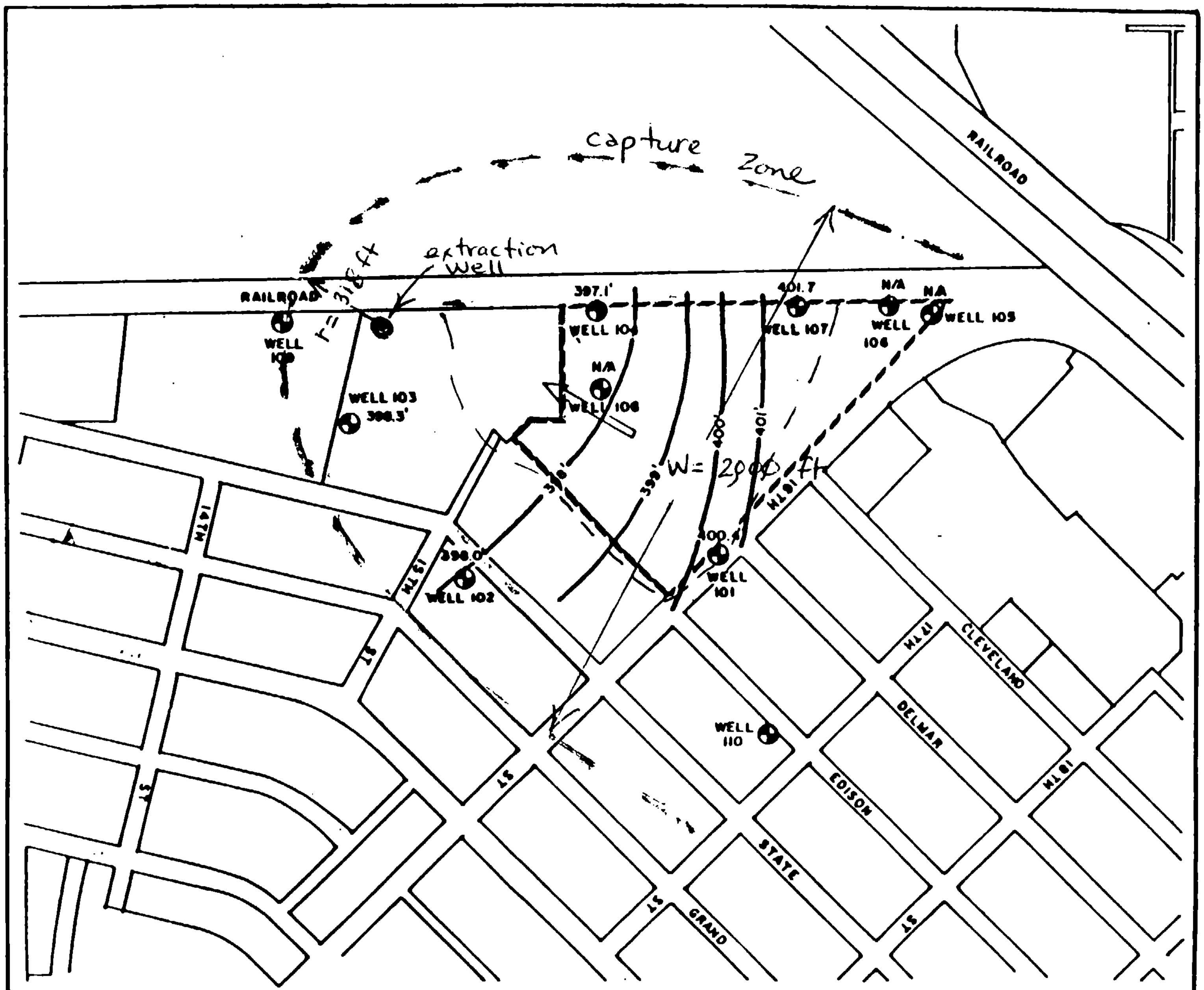
$h_w^2 = 5{,}642$ - $5{,}047$

$h_w =$ [illegible] $- 75$ ft

drawdown $= H - h_w = (90$ ft$) - h_w$

$=$ [illegible] ft

line of groundwater extraction wells



N

NL INDUSTRIES
GRANITE CITY SITE
GRANITE CITY, ILLINOIS

GROUNDWATER ELEVATION MAP

(SHALLOW WELLS)
10/87

LEGEND

401.15' WELL 101 — GROUNDWATER MONITOR WELL & GROUNDWATER ELEVATIONS FOR SHALLOW WELLS (10/87)

GROUNDWATER CONTOURS

GROUNDWATER FLOW DIRECTION

SITE PERIMETER

SCALE

300 0 300

FEET

O'BRIEN & GERE

FIGURE 10

Analytical Model for Estimation of Steady-State Capture Zones of Pumping Wells in Confined and Unconfined Aquifers

by Stuart Grubb[a]

Abstract

The analysis of capture zones of pumping wells is useful for designing pumping systems and wellhead protection programs. Using discharge potentials, equations are derived that can be applied to confined, unconfined, or combined confined and unconfined aquifers. The transient equations are transcendental and cannot be solved explicitly. However, infinite-time (steady-state) equations are presented which can be solved. They define an area in which, theoretically, all the water in the aquifer will eventually reach the pumping well, although the equations do not consider the effects of hydrodynamic dispersion. Equations for calculating the stagnation point, upgradient divide, and dividing streamline within the aquifer and an example problem are presented.

1. Introduction

A capture zone is defined as the area of an aquifer in which all the water will be removed by a pumping well or wells within a certain time period. Capture zone analysis has been recognized as an important consideration in the design of ground-water remediation systems and wellhead protection programs (Javandel and Tsang, 1986; Lee and Wilson, 1988). Bear and Jacobs (1965) investigated the movement of water particles injected into aquifers, and their analytical model is often used for determining capture zones as well. Several standard ground-water texts have simple equations for determining the infinite-time (steady-state) capture zone of a single well in a confined aquifer with uniform regional flow (for example, Bear, 1979; Todd, 1980). Equations can be superimposed to calculate the capture zone of multiple well systems (Javandel and Tsang, 1986), and computer models have been developed for analyzing multiple wells and heterogeneous aquifers (for example, McElwee, 1991). These models include the EPA's wellhead protection area (WHPA) package (EPA, 1990).

This paper presents a model for determining capture zones which is applicable not only to confined aquifers, but to unconfined and combined confined and unconfined aquifers as well. Portions of the model development were presented in Javandel and others (1985) and Bear and Jacobs (1965). These authors used the potential ($K\phi$) and the specific discharge to develop the equations. The primary difference in the model presented here is that the equations are generalized in terms of discharge potential so they can be used for confined aquifers, unconfined aquifers, and combined confined and unconfined aquifers by simply using the appropriate definition of one parameter, the discharge potential. The discharge potential concept was developed over 20 years ago and is fully documented in Strack (1989) and discussed by Marsily (1986), but it is not widely used.

2. Analytical Model

The assumptions for this model are as follows:

- The aquifer is homogeneous, isotropic, and infinite in horizontal extent.
- Uniform flow (steady-state) conditions prevail.
- A confined aquifer has a uniform transmissivity and no leakage through the upper or lower confining layers. An unconfined aquifer has a horizontal lower confining layer with no leakage, rainfall infiltration, or other vertical recharge. The effect of these assumptions is discussed later.
- Because the equations assume steady-state conditions, the storativity of a confined aquifer and the specific yield of an unconfined aquifer have been neglected. Hydrodynamic dispersion is also neglected.
- Dupuit assumption, i.e. vertical gradients are negligible.

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Received October 1991, revised February 1992, accepted March 1992.

Discussion open until July 1, 1993.

• The well is fully penetrating, is open over the thickness of the confined or unconfined aquifer at the well, and pumps at a constant rate.

Complex potentials are used to describe the distribution of discharge potentials throughout the aquifer. For background on the mathematics of complex potentials, Strack (1989, p. 269) gives a good, concise overview of the theory of complex functions. The complex potential for uniform regional flow in the (x, y) plane is

$$\Omega = -Q_0 z e^{-i\alpha} + C \qquad (1)$$

and the complex potential for a well is (Strack, 1989, p. 279)

$$\Omega = \frac{Q_w}{2\pi} \ln(z - z_w) + C \qquad (2)$$

where Q_0 = discharge vector of uniform flow; z = complex potential = $x + iy$; z_w = complex potential at the well; α = angle between the x axis and uniform flow; Q_w = discharge from the well; and C = constant which corresponds to the elevation of the bottom of the aquifer. Assume that $C = 0$. Note that

$$e^{-i\alpha} = \cos\alpha - i\sin\alpha \qquad (3)$$

and

$$Q_0 = Q_{x0} + Q_{y0} = \frac{d\Phi}{dx} + \frac{d\Phi}{dy} \qquad (4)$$

where Q_{x0} = x component of uniform flow; Q_{y0} = y component of uniform flow; and Φ = discharge potential.

The discharge potential is defined differently for confined, unconfined, and combined confined and unconfined aquifers as follows (Strack, 1989, p. 49):

Confined aquifer:	$\Phi = Kb\phi$
Unconfined aquifer:	$\Phi = \frac{1}{2}K\phi^2$
Combined confined and unconfined aquifer:	$\Phi = Kb\phi - \frac{1}{2}Kb^2$ for confined part
	$\Phi = \frac{1}{2}K\phi^2$ for unconfined part

where K = hydraulic conductivity; b = confined aquifer thickness; and ϕ = hydraulic head (or phreatic head) above the bottom of the aquifer. Writing equations in terms of discharge potentials is useful because the same equations may be used for all three types of aquifers by simply using the appropriate definition for Φ.

Because the complex potentials and the boundary conditions considered are linear and homogeneous, any linear combination of complex potentials can also be solved according to the principle of superposition. Superimposing (adding) the complex potentials for uniform flow and for flow to the pumping well gives

$$\Omega = \Phi + \Psi_i = -Q_0 z e^{-i\alpha} + \frac{Q_w}{2\pi} \ln(z - z_w) \qquad (5)$$

where Ψ = stream function.

The real and imaginary parts of (5) are

$$\Phi = -Q_0([x - x_w]\cos\alpha + [y - y_w]\sin\alpha) + \frac{Q_w}{4\pi}\ln([x - x_w]^2 + [y - y_w]^2) \qquad (6)$$

$$\Psi = Q_0([x - x_w]\sin\alpha + [y - y_w]\cos\alpha) + \frac{Q_w}{2\pi}\tan^{-1}\left(\frac{y - y_w}{x - x_w}\right) \qquad (7)$$

where x_w, y_w = x and y coordinates of the well.

The velocity components v_x and v_y in the x and y directions, respectively, along a particular streamline are

$$v_x = \frac{dx}{dt} = \frac{1}{Bn}\frac{d\Phi}{dx} = \frac{-Q_0\cos\alpha}{Bn} + \frac{Q_w[x - x_w]}{2\pi Bn([x - x_w]^2 + [y - y_w]^2)} \qquad (8)$$

$$v_y = \frac{dy}{dt} = \frac{1}{Bn}\frac{d\Phi}{dy} = \frac{-Q_0\sin\alpha}{Bn} + \frac{Q_w[y - y_w]}{2\pi Bn([x - x_w]^2 + [y - y_w]^2)} \qquad (9)$$

where n = porosity; t = time since pumping began; and B = aquifer thickness defined for different aquifers as follows

Confined aquifer:	$B = b$	
Unconfined aquifer:	$B = \phi$	
Combined confined and unconfined aquifer:	$B = b$	for confined part
	$B = \phi$	for unconfined part

For this problem assume that the uniform flow is in the direction of the x axis so that $\alpha = 0$. Equation (7) can then be written

$$x - x_w = [y - y_w]\,\mathrm{cotan}\,\frac{2\pi}{Q_w}(\Psi - Q_0[y - y_w]) \qquad (10)$$

Substituting (10) into (9) yields

$$dt = \frac{2\pi Bn}{Q_w}[y - y_w]\csc^2\frac{2\pi}{Q_w}(\Psi - Q_0[y - y_w])\,dy \qquad \ldots (11)$$

After integrating,

$$t = \frac{Bn[y - y_w]}{Q_0}\cot\frac{2\pi}{Q_w}(\Psi - Q_0[y - y_w]) + \frac{BnQ_w}{2\pi Q_0^2}\ln\sin\frac{2\pi}{Q_w}(\Psi - Q_0[y - y_w]) + f(\Psi) \qquad (12)$$

where $f(\Psi)$ is a constant dependent on the particular streamline considered. Equation (12) describes the time when water particles starting at a specific (x, y) coordinate along the streamline will reach the pumping well. When pumping first begins, the particles closest to the well will be captured immediately. In other words, $x = x_w$, $y = y_w$, $t = 0$ will be a solution to the equation. Therefore

$$f(\Psi) = \frac{-BnQ_w}{2\pi Q_0^2} \ln \sin \frac{2\pi}{Q_w} \Psi \tag{13}$$

Substituting (13) into (12) yields

$$t = \frac{Bn[y - y_w]}{Q_0} \cot \frac{2\pi}{Q_w} (\Psi - Q_0[y - y_w])$$

$$+ \frac{Bn}{2\pi Q_0^2} \ln \frac{\sin \frac{2\pi}{Q_w} (\Psi - Q_0[y - y_w])}{\sin \frac{2\pi}{Q_w} \Psi} \tag{14}$$

Substituting (7) into (14) yields

$$t = \frac{Bn[x - x_w]}{Q_0} - \frac{BnQ_w}{2Q_0^2}$$

$$\ln \frac{\sin\left(\frac{2\pi}{Q_w} Q_0[y - y_w] + \theta\right)}{\sin \theta} \tag{15}$$

where $\theta = \tan^{-1}([y - y_w]/[x - x_w])$.

Three dimensionless parameters may be introduced:

$$\bar{x} = \frac{2\pi Q_0}{Q_w}[x - x_w];\ \bar{y} = \frac{2\pi Q_0}{Q_w}[y - y_w];\ \bar{t} = \frac{2\pi Q_0^2}{BnQ_w} t \quad \ldots. (16)$$

Substituting (16) into (15) yields

$$\bar{t} = \bar{x} + \ln \frac{\sin\theta}{\sin(\bar{y} + \theta)} \tag{17}$$

or

$$e^{\bar{x} - \bar{t}} = \sin\bar{y} \frac{\bar{x}}{\bar{y}} + \cos\bar{y} \tag{18}$$

Bear and Jacobs (1965) provide additional analysis of equation (18) and its implications for ground-water transport in confined aquifers. Unfortunately, equation (18) is transcendental and cannot be solved explicitly for either x or y. Iterative solutions have been developed for solving special cases of the equation (for example, McElwee, 1991). These solutions are valid for unconfined aquifers as well if the dimensionless parameters introduced in equation (16) are used in equation (18).

3. Single Well in Uniform Flow at Infinite Time (Steady State)

A quick and simple analysis which is useful for many hydrogeologic projects is determining the capture zone of a single well in uniform flow at infinite time, or steady state. This will define an area in which all the water in the aquifer will reach the well if the well pumps for a sufficiently long time. At infinite time equation (18) can be simplified considerably and solved for x. The equations below give three critical parameters, the stagnation point, the upgradient divide, and the equation for the dividing streamline.

For simplicity, consider $x_w = 0$, $y_w = 0$, and $\alpha = 0$ as shown in Figure 1. The stagnation point is where $v_x = v_y = 0$. From equation (9) it is clear that $v_y = 0$ when $y = y_w = 0$. Substituting into equation (8) and solving for x yields

$$x_{STAG} = \frac{Q_w}{2\pi Q_0} \tag{19}$$

where x_{STAG} is the distance from the well to the downgradient stagnation point. As $\bar{t} \to \infty$, the equation for a streamline [equation (18)] becomes

$$\bar{x} = \frac{-\bar{y}}{\tan\bar{y}} \tag{20}$$

As $x \to \infty$ then $\tan y \to 0$, and $y \to N\pi$ where N = integer. Therefore, by equation (16), as $x \to \infty$

$$\bar{y} \to \frac{NQ_w}{2Q_0} \tag{21}$$

Substituting equation (21) into equation (7) with $x \to \infty$ yields

$$\Psi = \frac{NQ_w}{2} \tag{22}$$

The dividing streamline will approach the stagnation point. Substituting equation (22) and the coordinates of the stagnation point into equation (7) yields N = 1. Therefore, as $x \to \infty$, the dividing streamline will approach the line

$$y_{DIV} = \pm \frac{Q_w}{2Q_0} \tag{23}$$

which represents half the width of the capture zone far upgradient of the well. Considering that N = 1, substituting equation (16) into equation (20) yields the equation for the dividing streamline

$$x = \frac{y}{\tan\left(\frac{2\pi Q_0}{Q_w} y\right)} \tag{24}$$

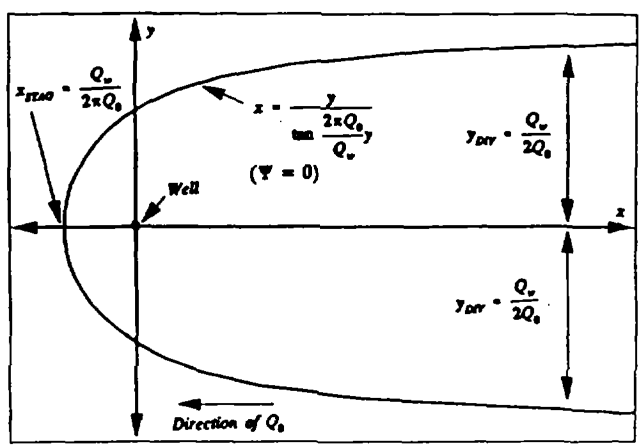

Fig. 1. Stagnation point, upgradient divide, and dividing streamline at infinite time (steady state).

The stagnation point, upgradient divide, and dividing streamline are shown on Figure 1. Because the direction of uniform flow for this problem is aligned with the x axis, $d\Phi/dy = 0$ and

$$Q_0 = \frac{d\Phi}{dx} \cong \frac{\Phi_1 - \Phi_2}{L} \tag{25}$$

where Φ_1 and Φ_2 = downgradient and upgradient discharge potentials, respectively, along a streamline before pumping begins; and L = distance between the locations where Φ_1 and Φ_2 were measured. The equations for the stagnation point, upgradient divide, and dividing streamline can be simplified into more common terms by substituting the above definition for Q_0 and the appropriate definitions for Φ. For a confined aquifer

$$x_{STAG} = \frac{Q_w}{2\pi Ti} \tag{26}$$

where i = natural hydraulic gradient = $d\phi/dx$ and T = aquifer transmissivity = Kb,

$$y_{DIV} = \pm \frac{Q_w}{2Ti} \tag{27}$$

and the dividing streamline is

$$x = \frac{y}{\tan\left(\frac{2\pi Ti}{Q_w}\, y\right)} \tag{28}$$

For an unconfined aquifer

$$x_{STAG} = \frac{Q_w L}{\pi K(\phi_1^2 - \phi_2^2)} \tag{29}$$

$$y_{DIV} = \pm \frac{Q_w L}{K(\phi_1^2 - \phi_2^2)} \tag{30}$$

and the dividing streamline is

$$x = \frac{y}{\tan\left[\frac{\pi K(\phi_1^2 - \phi_2^2)}{Q_w L}\, y\right]} \tag{31}$$

Equations (19), (23), and (24) can also be applied to combined confined and unconfined aquifers. To calculate Q_0 for this scenario, substitute the appropriate definition for Φ into equation (25) based on whether Φ was measured in the confined or unconfined part of the aquifer. For example, if Φ_1 is measured in the unconfined portion of the aquifer and Φ_2 is measured in the confined portion of the aquifer, then $\Phi_1 = \frac{1}{2}K\phi_1^2$ and $\Phi_2 = Kb\phi_2 - \frac{1}{2}Kb^2$. Substituting into equation (25) yields

$$Q_0 = \frac{K(\phi_1^2 - 2b\phi_2 + b^2)}{2L} \tag{32}$$

Note also that equation (6) may be used to obtain values of Φ throughout the aquifer by substituting the appropriate x and y coordinates. The effect of several pumping (or injection) wells on the value of Φ at any point in the aquifer may also be determined by using equation (6) and the principle of superposition. A separate equation for Φ is written for each well being considered based on its x_w, y_w, and Q_w. The separate equations are then added to yield one equation for Φ for any point in the aquifer.

4. Example Problem

The data for this example problem were adapted from a site in Wisconsin which formerly had a leaking underground storage tank. The leak had been detected shortly after it occurred, and a pumping well was to be installed to contain the spread of petroleum hydrocarbon contamination in the aquifer. The project hydrogeologist needed to determine the capture zone of the well as part of the pumping system design and evaluation.

In this example, the problem will be solved assuming the aquifer is confined [using equations (26)-(28)] and unconfined [using equations (29)-(31)], and the results will be compared. A site map is shown on Figure 2. Note that the x-axis has been aligned with the ground-water flow direction.

The aquifer and well characteristics are: Hydraulic conductivity (K) (determined from aquifer tests): 72 ft/day; Elevation of the lower confining layer: 1618.00 ft; Elevation of the upper confining layer (confined aquifer only): 1629.00 ft; Measured ground-water elevations in piezometers: P-1 = 1630.50 ft and P-2 = 1629.50 ft; Distance between P-1 and P-2 (L): 235 ft; Pumping rate (Q_w): 963 ft^3/day (5 gpm); ϕ_1 = 1630.50 ft − 1618.00 ft = 12.50 ft; and ϕ_2 = 1629.50 ft − 1618.00 ft = 11.50 ft. A cross section of the aquifer is shown on Figure 3.

For the confined aquifer:

$$b = 1629.00 \text{ ft} - 1618.00 \text{ ft} = 11.00 \text{ ft}$$

$$T = Kb = 790 \text{ ft}^2/\text{day}$$

$$i = \frac{\Phi_1 - \Phi_2}{L} = 0.00425$$

$$x_{STAG} = \frac{Q_w}{2\pi Ti} = 46 \text{ ft}$$

$$y_{DIV} = \pm \frac{Q_w}{2Ti} = \pm 140 \text{ ft}$$

and the dividing streamline is

$$x = \frac{y}{\tan\left(\frac{2\pi Ti}{Q_w}\, y\right)} = \frac{y}{\tan 0.022y}$$

For the unconfined aquifer:

$$x_{STAG} = \frac{Q_w L}{\pi K(\phi_1^2 - \phi_2^2)} = 42 \text{ ft}$$

$$y_{DIV} = \pm \frac{Q_w L}{K(\phi_1^2 - \phi_2^2)} = \pm 130 \text{ ft}$$

and the dividing streamline is

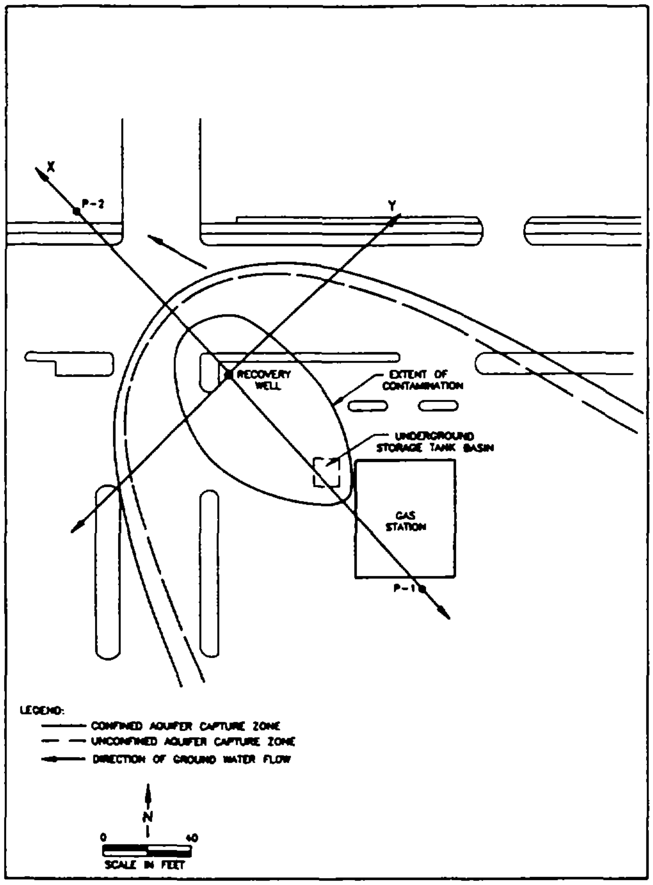

Fig. 2. Site map for the example problem showing the calculated capture zones.

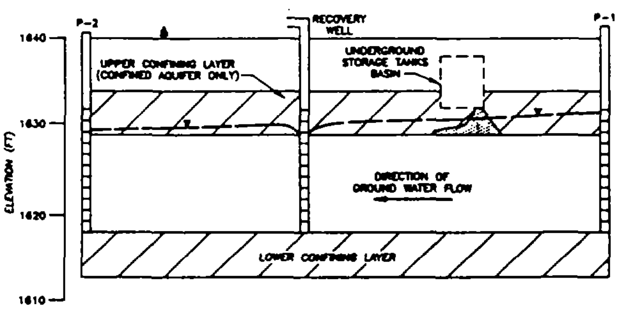

Fig. 3. Cross section of the aquifer along the x-axis.

$$x = \frac{y}{\tan\left[\dfrac{\pi K(\phi_1^2 - \phi_2^2)}{Q_w L}\, y\right]} = \frac{y}{\tan 0.024y}$$

The results of the analyses are shown on Figure 2.

5. Limitations of the Model

The steady-state equations presented in Section 1 neglect the influence of storativity and specific yield. The significance of this assumption decreases as pumping continues, and by definition storativity and specific yield = 0 at infinite time (steady state). Bear and Jacobs (1965) present a discussion of the effect of neglecting storativity for a confined aquifer with an injection well. They state that the actual front of the water injected from the well will lag behind the calculated front due to the storativity of the well and the aquifer. Similarly, in a pumping situation the actual capture zone will be somewhat smaller than the calculated capture zone due to the water being removed from storage.

The influence of water naturally added to or subtracted from the aquifer system other than regional uniform flow (leakage and infiltration) is not included in the equations. For unconfined aquifers, this may be a good assumption in urban areas or other areas where drainage systems prevent rainfall infiltration. If the addition of water to the aquifer through leakage and infiltration were considered in the equations, the result would be a smaller calculated capture zone.

The model is based on the Dupuit assumption, i.e., vertical gradients are negligible. For this reason, the model may not be accurate in areas of aquifer recharge or discharge, including the area near a well.

Hydrodynamic dispersion is commonly neglected from capture zone analyses. If dispersion were included in the analysis, there would not be a sharp capture zone boundary but rather a wide boundary with width proportional to the dispersion coefficient. Within the boundary only some fraction of the water particles would be captured by the well after a given time.

While the capture zone equations are clearly useful for solving problems related to contaminant transport or wellhead protection, it should be noted that the equations consider only advective flow. The solution to a contaminant transport problem must also incorporate the effects of dispersion, diffusion, sorption, degradation, and retardation.

6. Conclusions

Despite the assumptions and simplifications necessary to derive these equations, the equations can provide useful information for designing pumping systems or wellhead protection programs. Although they do not consider hydrodynamic dispersion, equations (26) through (31) are particularly useful for a quick analysis of critical properties of an aquifer and pumping system. While the many assumptions greatly restrict its applicability, users of the model should find many hydrogeologic problems of limited scope which could benefit from this analysis. The model presented in Section 2 is developed in terms of discharge potentials, which makes the equations applicable to confined, unconfined, and combined confined and unconfined aquifers. Previously derived capture zone equations (and computer programs) could also be modified and written in terms of discharge potentials to make them applicable to both confined and unconfined aquifers.

Computer Programs

A computer program is available which will solve and graph the capture zone equations in this paper. Included on the same computer diskette are spreadsheets for Lotus 1-2-3 and Quattro Pro which solve and graph these equations and other equations commonly used for well design and groundwater modeling. To order these programs, send a check or money order for $20 to Grubb Environmental Services, 2233 15th Avenue, North St. Paul, MN 55109. Please indicate whether you prefer 5.25-inch or 3.5-inch IBM formatted diskettes.

Acknowledgments

Thanks to Stephen Smith of GeoHydroCycle, Inc., John Baxter, Barry O'Flanagan, and Jim Prieur for reviewing this paper and to Linda Sax for drafting the figures.

Nomenclature

B	aquifer thickness [L];
b	confined aquifer thickness [L];
C	constant which corresponds to the elevation of the bottom of the aquifer;
i	natural ground-water gradient [L/L];
K	hydraulic conductivity [L/T];
L	distance between locations where Φ_1 and Φ_2 were measured [L];
n	porosity;
N	integer constant;
Q_0	discharge vector of uniform flow (L^2/T];
Q_w	discharge from the well [L^3/T];
Q_{x0}	x component of uniform flow [L^2/T];
Q_{y0}	y component of uniform flow [L^2/T];
t	time since pumping began [T];
T	aquifer transmissivity [L^2/T];
v_x	velocity component in the x direction [L/T];
v_y	velocity component in the y direction [L/T];
x_{STAG}	distance from the well to the downgradient stagnation point [L];
x_w	x coordinate of the well [L];
y_{DIV}	y coordinate of the dividing streamline far upgradient of the well [L];
y_w	y coordinate of the well [L];
z	complex potential x + iy;
z_w	complex potential at the well;
α	angle between the x axis and uniform flow;
θ	$\tan^{-1}([y - y_w]/[x - x_w])$;
Φ	discharge potential [L^3/T];
Φ_1	downgradient discharge potential [L^3/T];
Φ_2	upgradient discharge potential [L^3/T];
ϕ	hydraulic head (or phreatic head) above the bottom of the aquifer [L]; and
Ψ	stream function [L^3/T].

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